New Horizons in Astronomy: Frank N. Bash Symposium 2007
ASP Conference Series, Vol. 393, © *2008*
A. Frebel, J. R. Maund, J. Shen, and M. H. Siegel, eds.

Connecting the Dots: Low-Mass Stars, Brown Dwarfs, and Planets

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Abstract. The lowest mass object that Mother Nature makes through the process of "star formation" is currently unknown. While numerous very low-mass stars, brown dwarfs, and planets have been found, their relation to each other remains unclear. Here I describe how the study of brown dwarfs has the potential to help us understand both star and planet formation mechanisms. I describe the physical traits attributed to stars, brown dwarfs, and planets; compare the mass functions of brown dwarfs and planets; and discuss how studies of brown dwarfs in both young clusters and in the field can be used to challenge and constrain star and planet formation theories.

1. What are they and what do they look like?—Brown Dwarf Introduction

Over the past decade, there have been great advances in the exploration of the low-mass end of the main sequence including the discovery of brown dwarfs—star-like objects that are not massive enough to maintain hydrogen burning in their core. Two new spectral classes cooler than M (2200–4000 K) have been defined and characterized: the L (1400–2100 K) and T dwarfs (700–1300 K) (Kirkpatrick 2005, and references therein).

An artist rendition of three brown dwarfs compared to the Sun and Jupiter is shown in Figure 1. Due to the competing effects of coloumb repulsion ($R \propto M^{1/3}$) and electron degeneracy ($R \propto M^{-1/3}$) all very low-mass stars and brown dwarfs have a radius of $\sim 1\ R_{Jupiter}$. Also similar to Jupiter, L dwarf photospheres are dominated by condensate clouds. There is still a large temperature gap between the coolest observed T dwarf and Jupiter. Since brown dwarfs cool with time, there is good reason to expect a class of objects cooler than the T dwarfs likely comprised of the least massive and oldest brown dwarfs (see Figure 2. This class has been tentatively dubbed "Y" but no candidates have yet been found.

Unlike stars, brown dwarfs gradually cool and evolve down the spectral sequence as shown in Figure 2. A 0.075 $M_{\odot}$ object, just below the hydrogen-burning limit, will start as a mid-M dwarf at 3100 K, but after 10 Gyr, it will be a late-L dwarf at 1300 K. Similarly, a 7 $M_{Jupiter}$ (0.007 $M_{\odot}$) object that is first visible as an early-L dwarf at 2200 K is only 400 K after 10 Gyr—significantly cooler than the latest T dwarf. Thus, there is no mass-luminosity relation for brown dwarfs as there is for stars. In addition, not all M and L dwarfs are brown dwarfs. Current theories suggest that all objects cooler than about spectral type

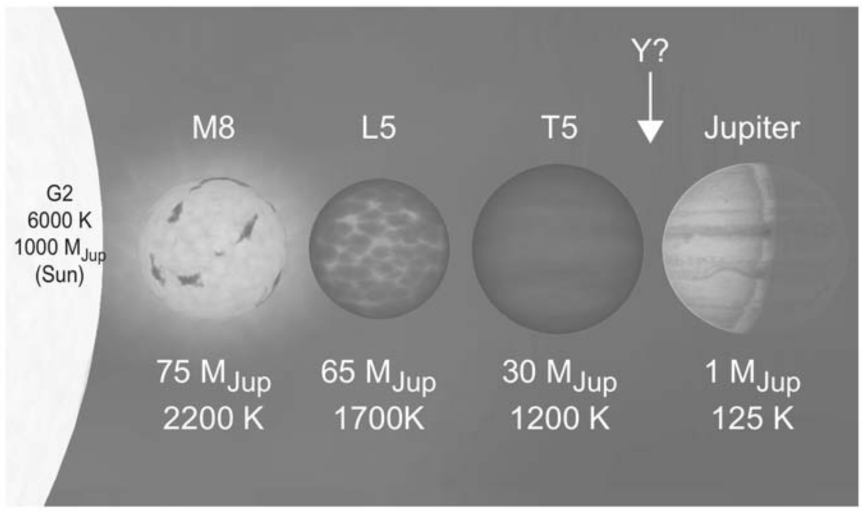

Figure 1. Artist rendition of the Sun, a late-M dwarf, an L dwarf, a T dwarf, and Jupiter. The M, L, and T dwarfs are shown at the age of 1 Gyr and all of the objects are shown on the same physical scale. Illustration by Dr. Robert Hurt of the Infrared Processing and Analysis Center.

L4 are brown dwarfs while mid-M to early-L dwarfs are a mix of stars and young brown dwarfs (Burrows et al. 2001).

While brown dwarfs were first hypothesized to exist in the 1960s (Kumar 1963a,b; Hayashi & Nakano 1963), it was not until the 1980s and the advent if infrared-sensitive CCDs that late-M dwarfs began to be discovered in significant numbers (Reid & Gilmore 1981; Probst & Liebert 1983; Hawkins & Bessell 1988; Bessell 1991). At the time, these objects were thought to be very low-mass stars, not brown dwarfs. It turns out the first L dwarf, GD 165B, was discovered in 1988, but nobody was sure what it was (Becklin & Zuckerman 1988; Kirkpatrick et al. 1993).

Finally in 1995, two objects were identified that were generally accepted to be the first brown dwarfs. Gl 299B was identified and with strong CH_4 absorption bands (the signature feature of the T dwarf class), was confirmed as the first brown dwarf found in the field and the first T dwarf (Nakajima et al. 1995; Oppenheimer et al. 1995). Tiede 1 is a late-type M dwarf with lithium absorption discovered in the Pleiades. Based on the measured abundance of lithium and the age of the Pleiades, Tiede 1 was the first young brown dwarf found (Rebolo et al. 1995, 1996). The spectral sequence was formally extended to include types L and T in 1999 by Kirkpatrick et al.. As of October 2007 there were 500 L dwarfs and 120 T dwarfs listed on the brown dwarf online repository.[1]

Since the discovery of brown dwarfs, there has been substantial debate surrounding the formation of brown dwarfs and several contentious assertions have been made:

- *Brown dwarfs must form differently than stars because they are so much lighter than the Jeans Mass.* Star formation theory cannot easily produce low mass objects and as a result, other theories have been put forward to explain the existence of low-mass stars and brown dwarfs.

- *Objects below 13 $M_{Jupiter}$ could not possibly have formed as stars and therefore must be planets.* The Shu et al. (1987) model for low-mass star formation relies on deuterium burning to start convection which then produces the stellar winds necessary to halt the infall of the collapsing proto-star. As shown in Figure 2, objects more massive than 13 $M_{Jupiter}$ (solid lines) burn deuterium causing their temperatures at young ages to plateau; objects with masses below 13 $M_{Jupiter}$ (dashed lines) do not burn deuterium and cool rapidly during their first 50 Myr. As a result, it has been proposed that a mass of 13 $M_{Jupiter}$ be the delineation between planets and brown dwarfs.

- *Brown dwarfs are proto-star cores whose accretion was halted due to being ejected from the nebula.* This theory, proposed by Reipurth & Clarke (2001), provides a different scenario for halting the accretion onto the proto-star and predicts truncated and/or missing disks around brown dwarfs.

One discovery in particular has challenged brown dwarf formation theories and shed light on properties that might be useful for distinguishing planets from brown dwarfs. Gizis (2002) identified 2MASS J12073346−3932539 (hereafter 2M1207−39), a M8 brown dwarf in the ∼10 Myr-old TW Hydrae Association (TWA) with an estimated mass of ∼25 $M_{Jupiter}$ (Mohanty & Basri 2003). Chauvin et al. (2004) detected a ∼5–10 $M_{Jupiter}$ mid-to-late L dwarf companion (hyped as the first direct detection of an exo-planet) with a ∼70 AU separation from the primary. Also, the primary has a disk, is actively accreting, and does not support the ejection model for brown dwarf formation (Riaz et al. 2006; Mohanty et al. 2007). The planetary-mass secondary could not have formed in the disk of the primary due to the wide separation and the (relatively) large mass of the secondary (compared to the mass expected to be in the primary's disk). In most respects, this system appears to have formed in the same way as a binary star system even though the secondary is well below the 13 $M_{Jupiter}$ deuterium burning limit. The 2M1207−39 system has demonstrated: 1) the mass and temperature regimes of planets and brown dwarfs indeed overlap; 2) observables such as separation and mass ratio point toward either a planet or star

[1]http://www.dwarfarchives.org

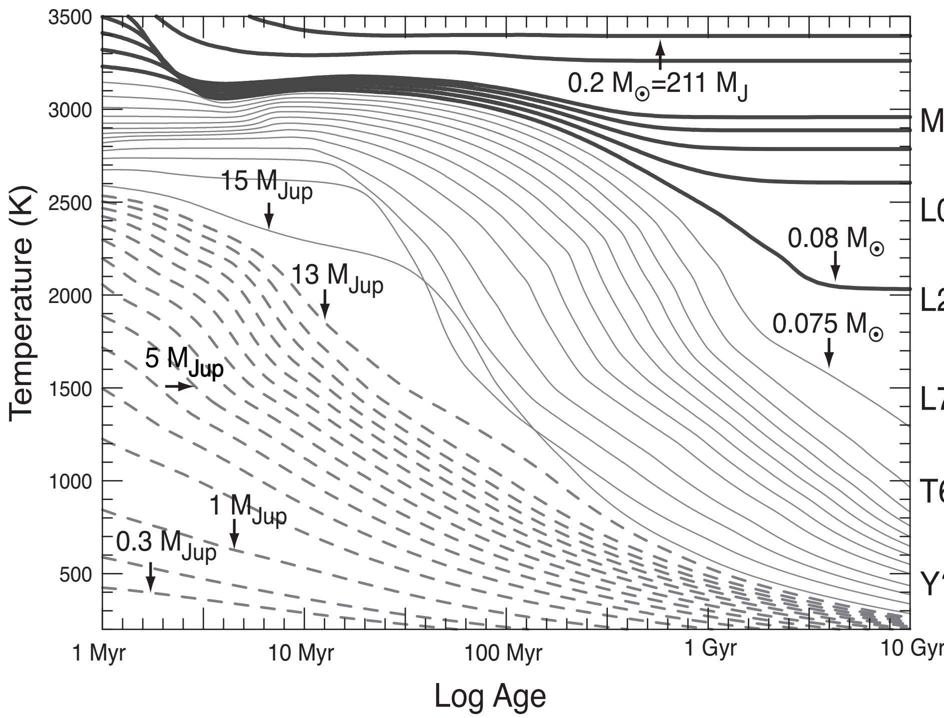

Figure 2. Effective temperature evolution of low-mass stars (*thick lines*), brown dwarfs (*thin lines*) and planetary-mass brown dwarfs (*dashed lines*). Adapted with permission from Burrows et al. (2001). Copyright by the American Physical Society (DOI: 10.1103/RevModPhys.73.719).

formation scenario; and 3) the disks and companions of nearby, intermediate-age brown dwarfs might play an important role in determining the range of properties spanned by planetary-mass objects regardless of formation method.

2. How many are there?—Brown Dwarf and Planet Luminosity and Mass Functions

The field luminosity function of the Solar Neighborhood (8 and 20 pc) is shown in the left panel of Figure 3. M dwarfs are by far the most numerous stellar constituents of the Solar Neighborhood. The L dwarf luminosity function (shaded) is composed of both stars and brown dwarfs and has only recently been measured (Cruz et al. 2003, 2007). These new data show that the luminosity function continues to decline sharply beyond $M_J = 10$ and reaches a minimum at $M_J \sim 13$. Formally, these results indicate that the space densities remain constant at fainter magnitudes, however, since the measurements are lower limits (as indicated by arrows) the luminosity function likely increases for $M_J > 14$.

Simulated luminosity functions with different underlying mass functions for brown dwarfs and the lowest-mass stars from Allen et al. (2005) are shown in

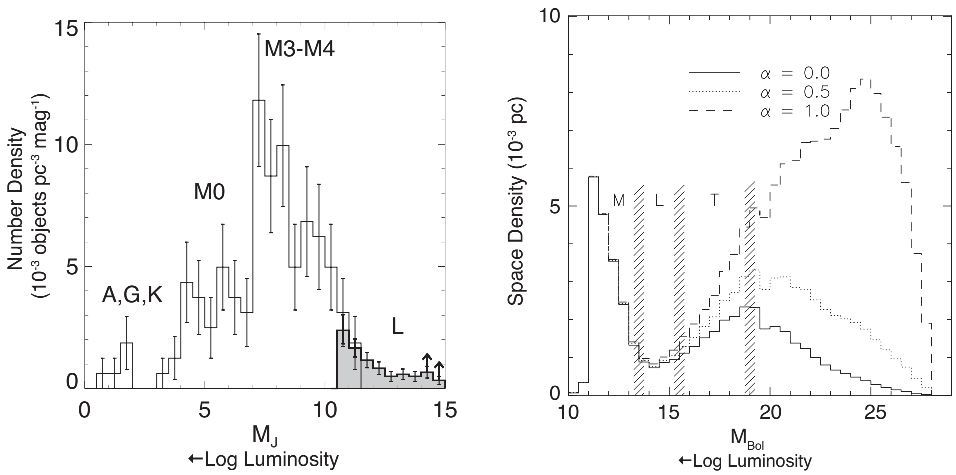

Figure 3. *Left*: *J*-band luminosity function of the Solar Neighborhood based on an 8-pc sample (Reid et al. (2003), *unshaded*) and a 20-pc sample for the coolest objects (Cruz et al. (2007), *shaded*). The last two magnitude bins are incomplete and the lower limits on the space densities are indicated with arrows. *Right:* Simulated luminosity functions of low-mass stars and brown dwarfs derived assuming underlying mass functions with different α parameters. Recent T dwarf space densities indicate $\alpha \sim 0.5$. Adapted from Allen et al. (2005) and reproduced by permission of the American Astronomical Society (DOI: 10.1086/429548).

the right panel of Figure 3. Unfortunately, the L dwarf luminosity function does not constrain the underlying mass function and T dwarf space densities are required. Estimates of T dwarf space densities indicate $\alpha \sim 0.5$ (Burgasser et al., in preparation) and imply that Y dwarfs are not very numerous. Reliable discrimination between different models for the underlying mass function must await observational surveys that probe brown dwarfs at temperatures below 600 K, likely near the boundary between T and Y dwarfs.

The overall morphology of the *J*-band luminosity function for $M_J < 10$ (unshaded histogram in the left panel of Figure 3) reflects the convolution of the underlying mass function and the M_J-mass relation. Qualitatively, the luminosity function increases for $0 < M_J < 7$ since the mass function increases with decreasing mass ($\alpha = 2.35$ at high masses and 1 at lower masses). At fainter magnitudes, the *J*-band luminosity function turns over not because the mass function changes drastically, but because the slope of the M_J-mass relation changes; while $\delta\text{mass}/\delta M_J \sim 0.4 M_\odot$ mag^{-1} for $M_J < 7$, $\delta\text{mass}/\delta M_J \sim 0.07 M_\odot$ mag^{-1} for $7 < M_J < 10$ (Delfosse et al. 2000).

The morphology of the luminosity function for $M_J > 10$ (right panel of Figure 3 and the shaded histogram in the left panel) is due to the mix of stars and brown dwarfs in the ultracool regime and is qualitatively in accord with theoretical expectations. The drop in number density with increasing magnitude reflects a further contraction in $\delta\text{mass}/\delta M_J$. The population of the very lowest mass stars that appear as L dwarfs span an extremely small range in mass

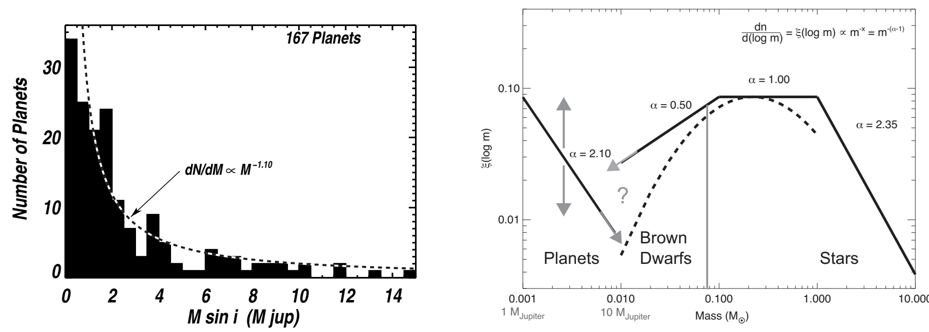

Figure 4. *Left:* Minimum mass distribution of the 167 known radial velocity planets. Originally in Butler et al. (2006) and reproduced by permission of the American Astronomical Society (DOI: 10.1086/504701). *Right:* Mass functions of stars, brown dwarfs, and planets represented as segmented power-laws (*solid black lines*) and the lognormal system mass function found by Chabrier (2003) (*dashed line*). The lowest mass brown dwarf, the highest mass planet, and the absolute scale for the planet mass function are unknown.

$(0.075 < M < 0.085 M_\odot)$ and, as a result, are rare. The brown dwarfs in this effective temperature regime are relatively young and are at the high-mass extreme, near the hydrogen-burning limit. Brown dwarfs dominate the counts beyond $M_J > 13.5$, and the upturn in number densities reflects the slowdown in cooling rates at lower temperatures. For example, a 0.07 $M_\odot$ brown dwarf takes 2.7 Gyr to evolve down the L dwarf sequence, but remains a (cooling) T dwarf (T_{eff} 1400–600 K) for 30 Gyr, or more than two Hubble times; a low-mass, 0.025 $M_\odot$ brown dwarf spends only 120 Myr as an L dwarf, but 1.5 Gyr as a T dwarf (Burrows et al. 2001).

The mass distribution of radial velocity planets is shown in the left panel of Figure 4. Despite the numerous biases and selection effects, the mass function of planets is strongly increasing toward smaller masses. The best estimates for the mass functions of stars, brown dwarfs, and planets is shown in the right panel of Figure 4 (solid lines). The absolute normalization of the planet mass function is not yet known: Are there more or less planets than brown dwarfs? Also unknown are the masses of the highest-mass planet and the lowest-mass brown dwarf, however it is likely that the mass regimes overlap. The very different mass distributions of the radial velocity planets and brown dwarfs (increasing versus decreasing toward lower mass) indicate two independent populations with different formation mechanisms and probably other observable differences.

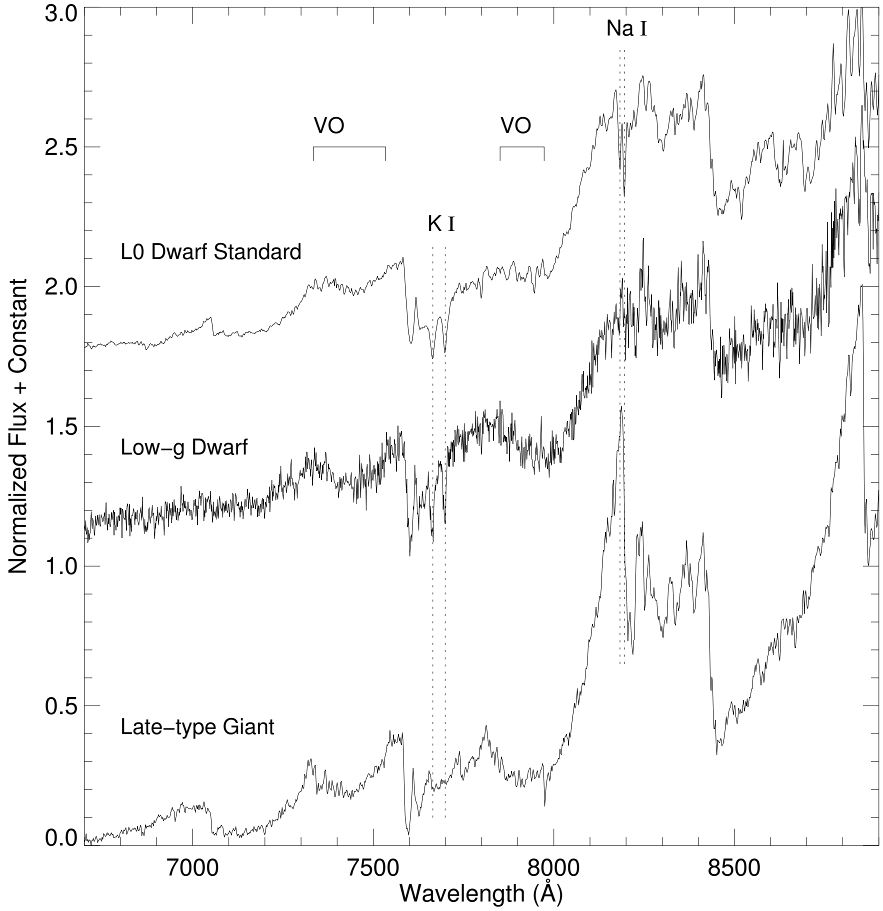

Figure 5. Optical spectra of a normal L0 dwarf, a low-gravity dwarf, and a late-type giant (*top-to-bottom*). The VO, K I, and Na I absorption strengths of the low-gravity dwarf are between the normal dwarf and the giant.

3. What can they tell us?—A New Population of Juvenile Brown Dwarfs

Until recently, studies of brown dwarfs (BD) have largely focused on two stages of evolution: the very young (∼1 Myr, e.g., Taurus) and the mature ($\gtrsim$1 Gyr). Brown dwarfs in young clusters are studied because they are still fairly luminous (typically M type) and the age of the cluster can be adopted for the brown dwarf. A major drawback of these clusters is their rather large distance from the Sun (∼100–500 pc) and reliably identifying the lowest-mass components of these clusters has proven to be a significant observational challenge.

We believe that we have uncovered a nearby (∼30–60 pc), juvenile (5–50 Myr) population of brown dwarfs that mediate the current bi-polar situation. The youth of our targets is inferred from the presence of conspicuous low-gravity features in their optical and/or near-infrared spectra not seen in hundreds of other M and L dwarfs; one example is shown in Figure 5. Compared to old field dwarfs of similar spectral type (equivalent temperature), low gravity is indicative of both a lower mass and larger radius—hallmarks of young brown dwarfs still undergoing gravitational contraction. The spectral features present in our targets are similar to those seen in members of very young clusters (e.g., Taurus) but since none of our targets are near any tightly bound groups, they are most certainly older than 1 Myr. The upper limit on our age estimate is based on the stronger low-gravity spectral features exhibited in our targets than those seen in members of 100 Myr old clusters (e.g., Pleiades).

Figure 6 shows the location of our candidate young brown dwarfs (five-pointed stars) with confirmed members of the 8–50 Myr nearby associations AB Dor, β Pic, Tuc/Hor, and TWA as identified by Zuckerman & Song (2004). The spatial distributions of the two populations, widely distributed and clumped in the south, are suggestively similar. This is not too surprising since the age and distance estimates of our young brown dwarfs are consistent with those of the moving groups.

Our new-found population of brown dwarfs with older ages has the potential to lend insight on disk evolution and planet formation. It is now known that it is not unusual for young brown dwarfs to harbor disks and there is evidence that brown dwarf disks are longer lived than those of more massive stars (Carpenter et al. 2006; Scholz et al. 2007). Any disks found around juvenile objects are particularly interesting because their age is coincident with the epoch of planet formation (10–30 Myr). Our candidates are currently being targeted with Spitzer IRAC and 24 μm imaging to investigate the frequency and properties of brown dwarf disks at juvenile ages.

The new population is also ideal for searching for planetary-mass companions — counterparts to the 2M1207−39 system. Tight systems more easily resolved due to their relative proximity (within 60 pc). Additionally, since the objects are still fairly young, they have not cooled too much and are still relatively bright compared to their older counterparts of the same mass.

To confirm that our candidates are both young and members of the southerly associations, significant follow-up observations are being undertaken. High signal-to-noise spectra covering 0.8–2.5 μm is being compiled for all of the young candidates in order to fully study the low-gravity spectral features. Proper motions, radial velocities and trigonometric parallaxes are being obtained in order to derive accurate space motions and determine cluster membership.

Acknowledgments. The results discussed are a result of efforts undertaken with my collaborators Adam Burgasser, Jackie Faherty, Davy Kirkpatrick, Dagny Looper, Eric Mamajek, Subhanjoy Mohanty, Lisa Prato, and Neill Reid. Support for this work was provided by NASA through the Spitzer Space Telescope Fellowship Program, through a contract issued by the Jet Propulsion Laboratory, California Institute of Technology under a contract with NASA. I would particularly like to thank the conference organizers and the other invited speakers for their hard work and for making the conference a success. Many thanks to the McDonald Observatory and Astronomy Department Board of Visitors for their generous support of this unique and symposium—I am very grateful to have been a part of it.

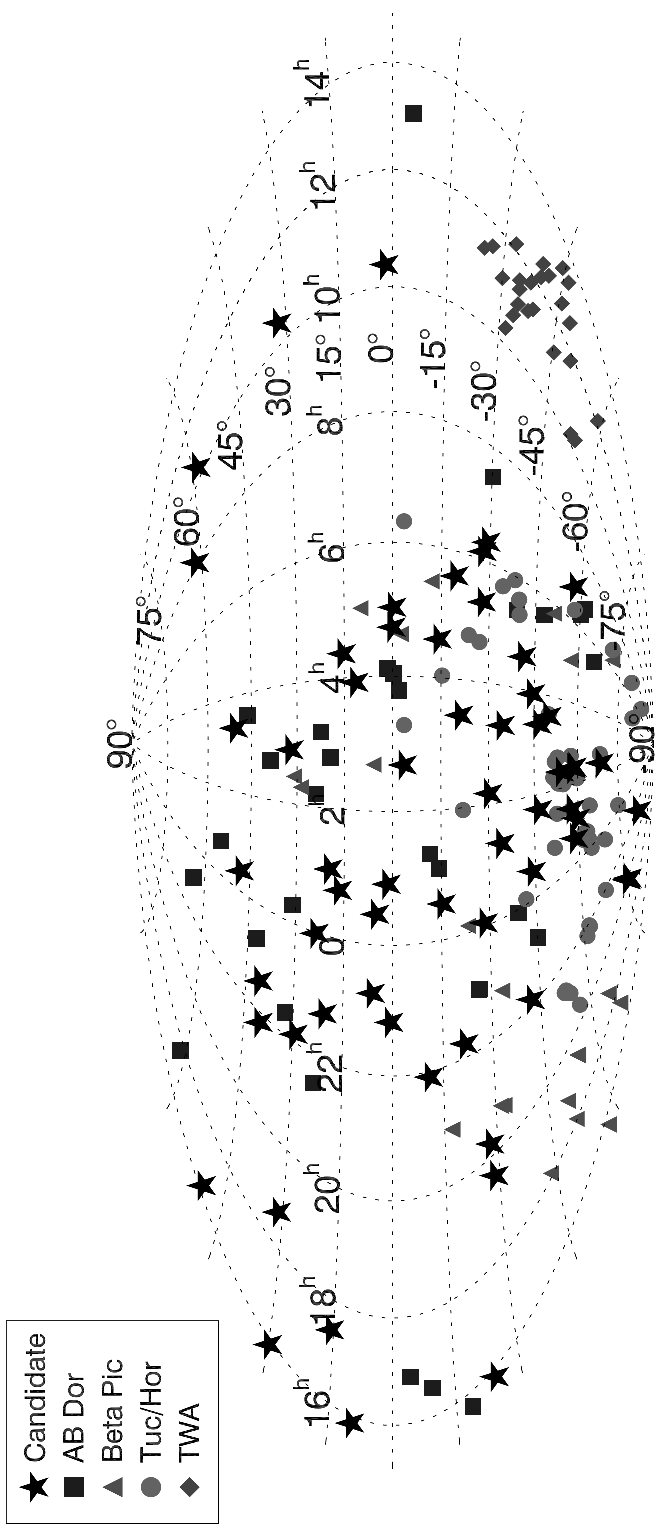

Figure 6. Celestial distribution of young brown dwarf candidates (*five-pointed stars*) on the sky. Also shown are known members of the AB Dor (*squares*), β Pic (*triangles*), Tuc/Hor (*circles*), and TWA (*diamonds*) young stellar associations (Zuckerman & Song 2004).

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